Recent progress in (Core-collapse) supernova progenitor theories

Hideyuki Umeda

collaborators: T. Yoshida, K. Takahashi, T. Urushibata

Dept of Astronomy, Univ of Tokyo

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1. Explodability of progenitors

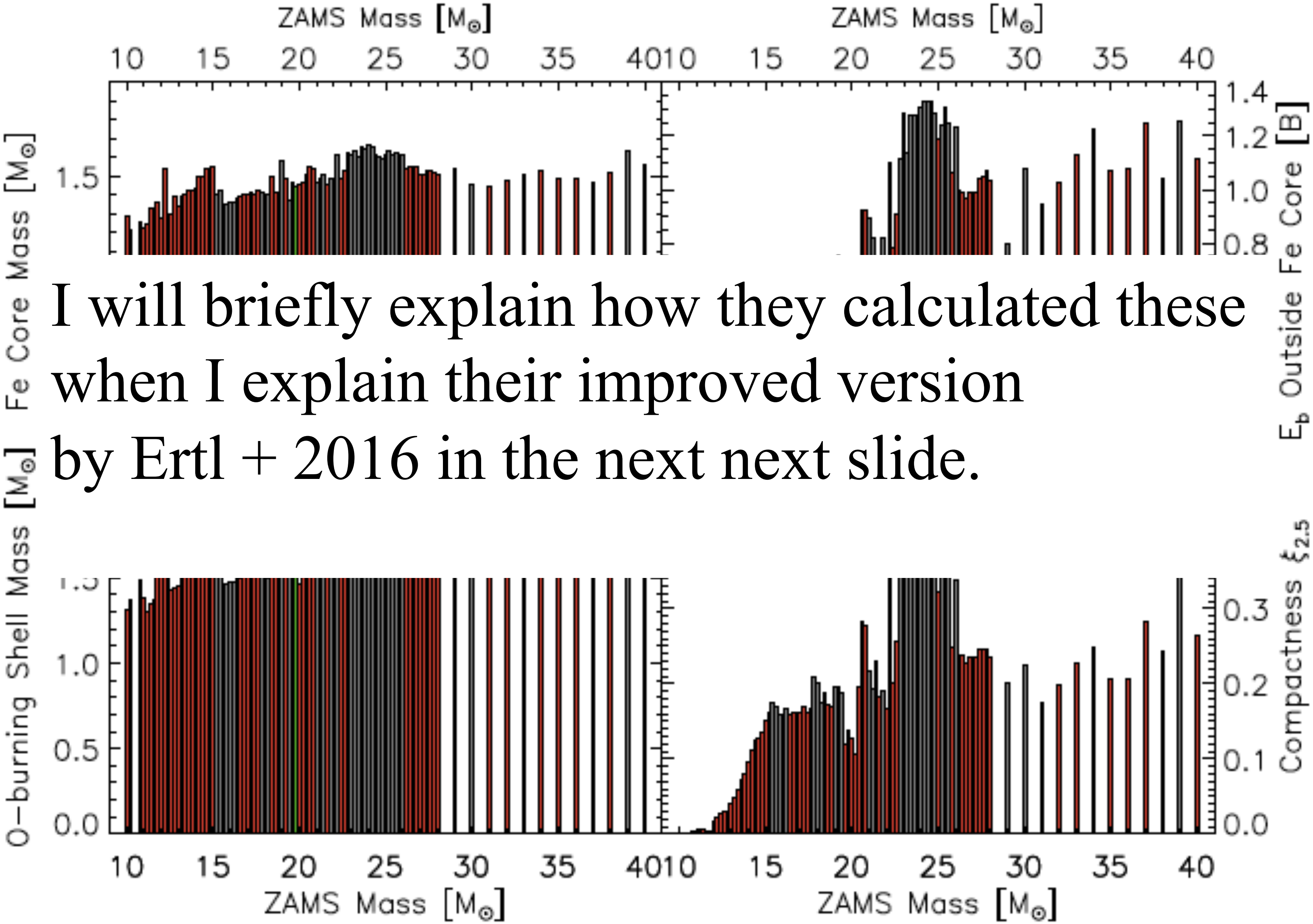
- We used to say that M ~ 10-25$M_\odot$ stars explode as supernovae (with leaving neutron stars), and M > ~ 25$M_\odot$ stars don't (with leaving blackholes).

- Recent theoretical studies have suggested that the situation could be more complicated.

Explodability of progenitors

- Multi-D simulations of CCSNe (due to neutrino driven mechanism) have been significantly progressed, but
  - Explosion energy is too small – Missing something (physics)?
  - Explodable mass range is not clear:
    - Traditional Fe core mass is not so good to discuss explodability
    - O'Connor & Ott (2011) --- new indicator ξ (compactness parameter)
      $\xi_M = (M/M_\odot) / (R(M)/1000\text{ km})$, measured @core bounce time
      ($\xi_{2.5} > 0.45$ for non-explosion)
    - But this is also not so good (e.g., Ugliano+2012)
      - Undetermined for $0.15 < \xi_{2.5} < 0.35$
      - ξ_M is also not so useful because it is calculable only AFTER a collapse simulation

Ugliano, Janka + (2012, ApJ)   (1D study)



I will briefly explain how they calculated these when I explain their improved version by Ertl + 2016 in the next next slide.

Explodability of progenitors

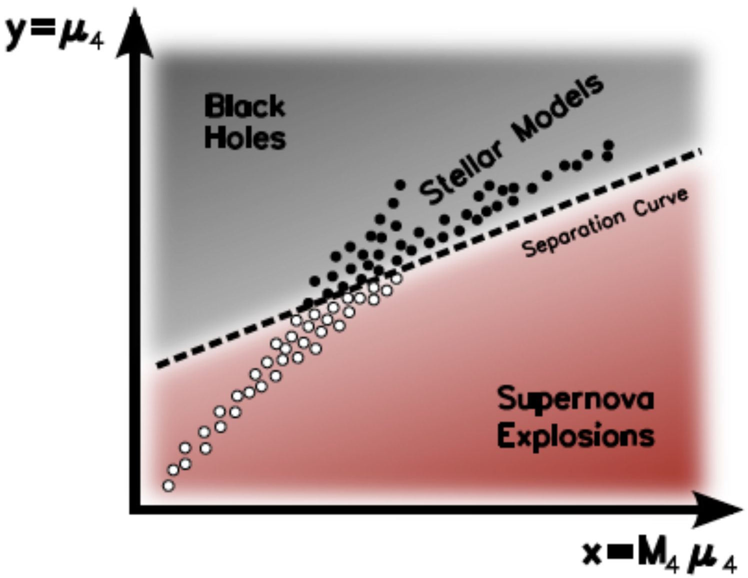
- Explodable mass range is also observationally uncertain
  - It appears no SN IIp above M ~ 18 $M_{\odot}$ (Smartt + 2009)
    - Traditionally considered that M < ~25 $M_{\odot}$ become SN IIp
  - This may be explained if $\xi_{2.5} < 0.2$ progenitors do not explode (Horiuchi + 2014) --- (SN1987A, M~ 20$M_{\odot}$?

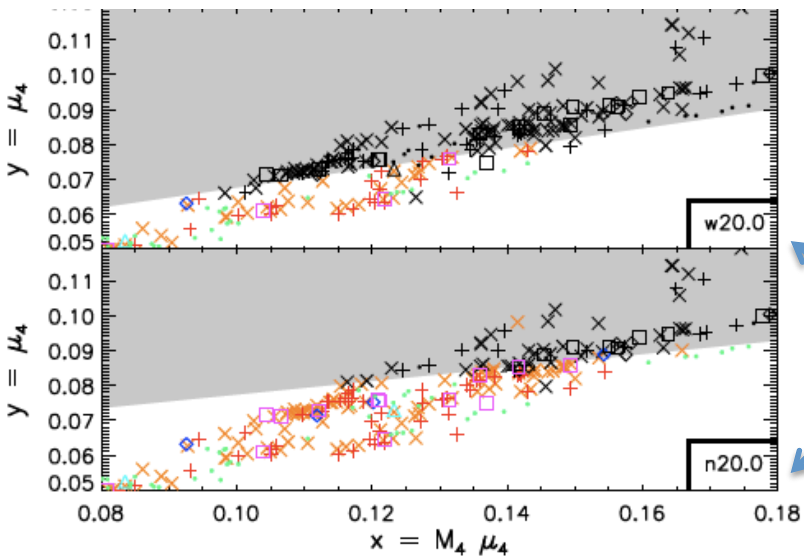
Explodability of progenitors : A possible better indicator

Ertl, Janka + 2016, arXiv: 1503.07522 (Two parameter criterion)

- 1D model + given PNS core cooling model (for $M_r < 1.1 M_\odot$)
  + calibration to SN1987A (+progenitor dependent accretion L
  621 progenitor models used
- Two (Pre-collapse) parameters are important: M_4 and μ_4
  M_4 ($M_\odot$) = enclosed mass inside entropy per nucleon s=4
  (may be replaced by Fe core mass)
  μ_4 = $(dM / M_\odot) / (dr / 1000\mathrm{km})$ @s=4 (mass derivative)

μ_4 correlates with mass accretion rate, and $M_4\, \mu_4$ with neutrino luminosity





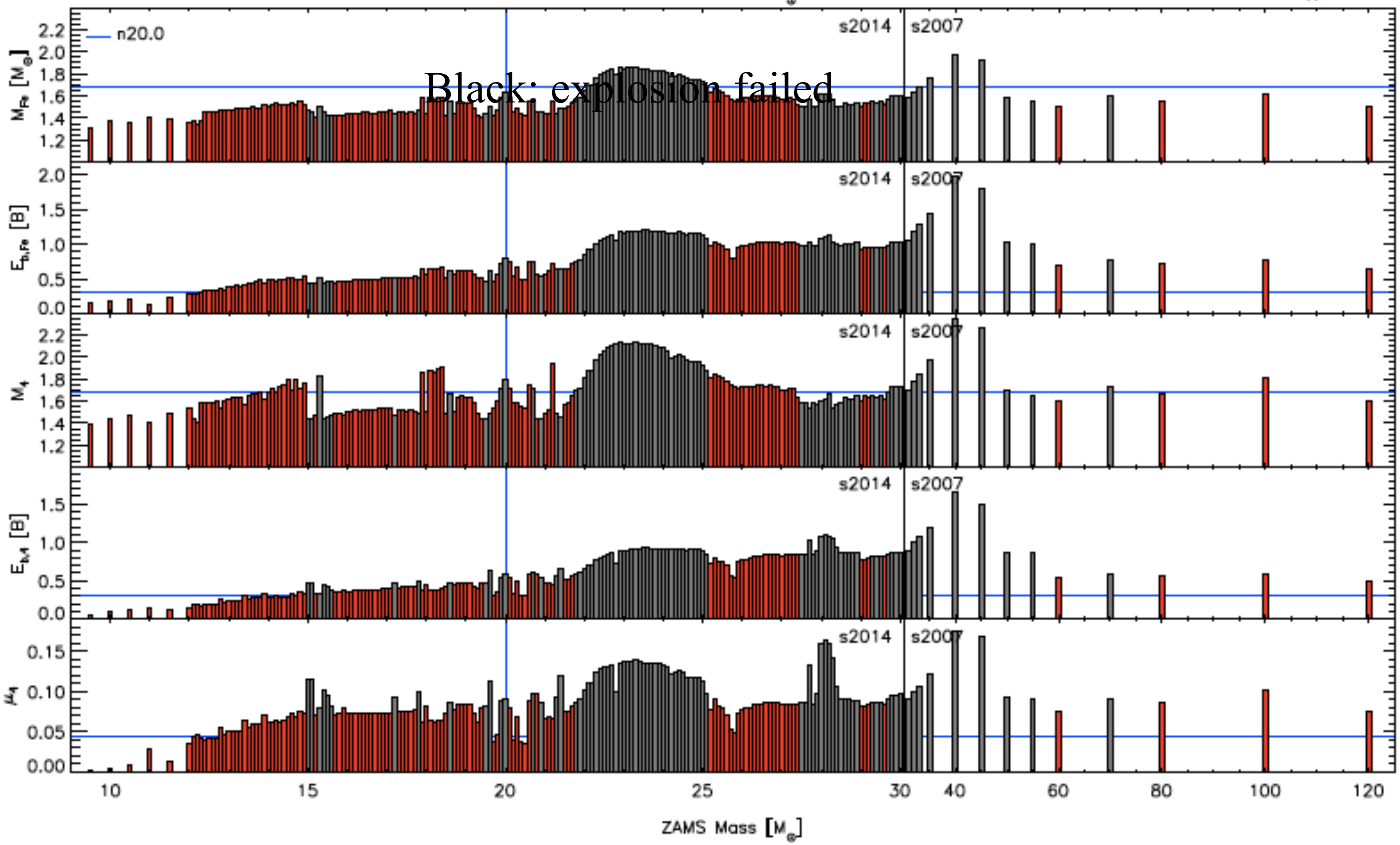
Actual calculations

Colored: success

PNS model name

Ertl + 2016 : results

- Critical line : $\mu_4 = k_1 (M_4 \mu_4) + k_2$
- k_1 and k_2 depends on PNS models (unfortunately!)
- It seems two separated explosion regions ($M < 22$ & $25\text{-}27_\odot$)



Ertl + 2016 : Is this result different from what we thought?

- Possible interpretation
  - Most 10 < $M/M_\odot$ < 22 stars ➡ Type II supernova (with NSs)
  - 22 < $M/M_\odot$ < 25 ➡ blackholes
  - 25 < $M/M_\odot$ < 27 ➡ explosion (Faint supernova with Hydrogen)
  - 27 < $M/M_\odot$ ➡ mostly blakhole (some of them are hypernova?)

- These may be consistent with observations (except for the lack of massive SN IIp suggested by Smartt + 2009)

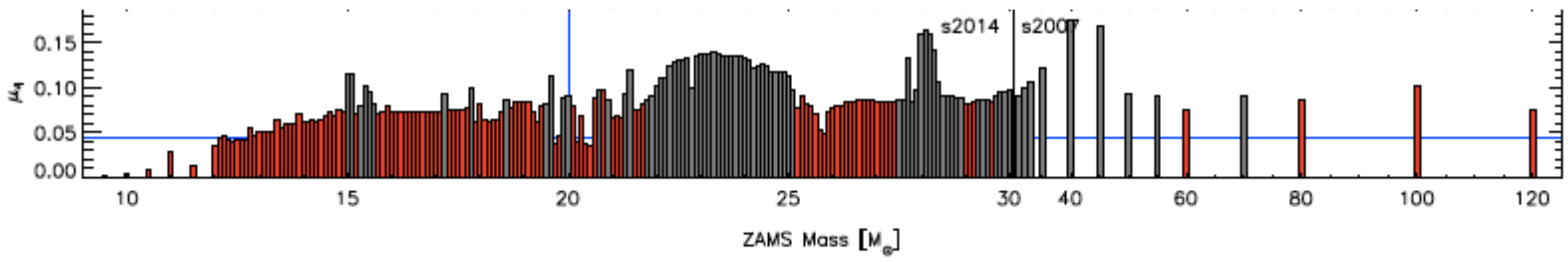


TABLE 1

CALIBRATION MODELS WITH EXPLOSION AND REMNANT PROPERTIES

Calibration Model	$\xi_{1.5}$ [a]	$\xi_{1.75}$ [a]	$\xi_{2.0}$ [a]	$\xi_{2.5}$ [a]	t_{exp} [b] [ms]	E_{exp} [c] [B]	M_{ej} [d] [$M_\odot$]	E_{exp}/M_{ej} [B/$M_\odot$]	$M_{^{56}Ni}$ [e] [$M_\odot$]	M_{tracer} [f] [$M_\odot$]	M_{ns} [g] [$M_\odot$]	M_{wind} [h] [$M_\odot$]	M_{fb} [i] [$M_\odot$]	$t_{\nu,90}$ [j] [s]	$E_{\nu,tot}$ [k] [100 B]
s19.8 (2002)	1.03	0.35	0.22	0.14	750	1.30	12.98	0.100	0.072	0.034	1.55	0.096	0.00298	4.27	3.68
w15.0	0.34	0.09	0.03	0.01	580	1.41	13.70	0.103	0.045	0.046	1.32	0.088	0.00018	5.18	2.81
w18.0	0.76	0.26	0.16	0.10	730	1.25	15.42	0.081	0.056	0.036	1.48	0.081	0.00310	4.16	3.32
w20.0	0.98	0.35	0.18	0.06	620	1.24	17.81	0.070	0.063	0.027	1.56	0.089	0.00168	4.73	3.61
n20.0	0.87	0.36	0.19	0.12	560	1.49	14.84	0.100	0.036	0.052	1.55	0.117	0.00243	3.97	3.48

BH-SN SEPARATION CURVES FOR ALL CALIBRATION MODELS

Calibration Model	k_1 [a]	k_2 [a]	M_4 [b]	μ_4 [b]	$M_4\mu_4$ [b]
s19.8 (2002)	0.274	0.0470	1.529	0.0662	0.101
w15.0[c]	0.225	0.0495	1.318	0.0176	0.023
w18.0	0.283	0.0430	1.472	0.0530	0.078
w20.0	0.284	0.0393	1.616	0.0469	0.076
n20.0	0.194	0.0580	1.679	0.0441	0.074

[a] Fit parameters of separation curve (Eq. 9) when x and y are measured for a central stellar density of 5×10^{10} g cm^{-3}.

[b] Measured for a central stellar density of 5×10^{10} g cm^{-3}.

[c] M_4 and μ_4 measured roughly at core bounce, because pre-collapse data are not available.

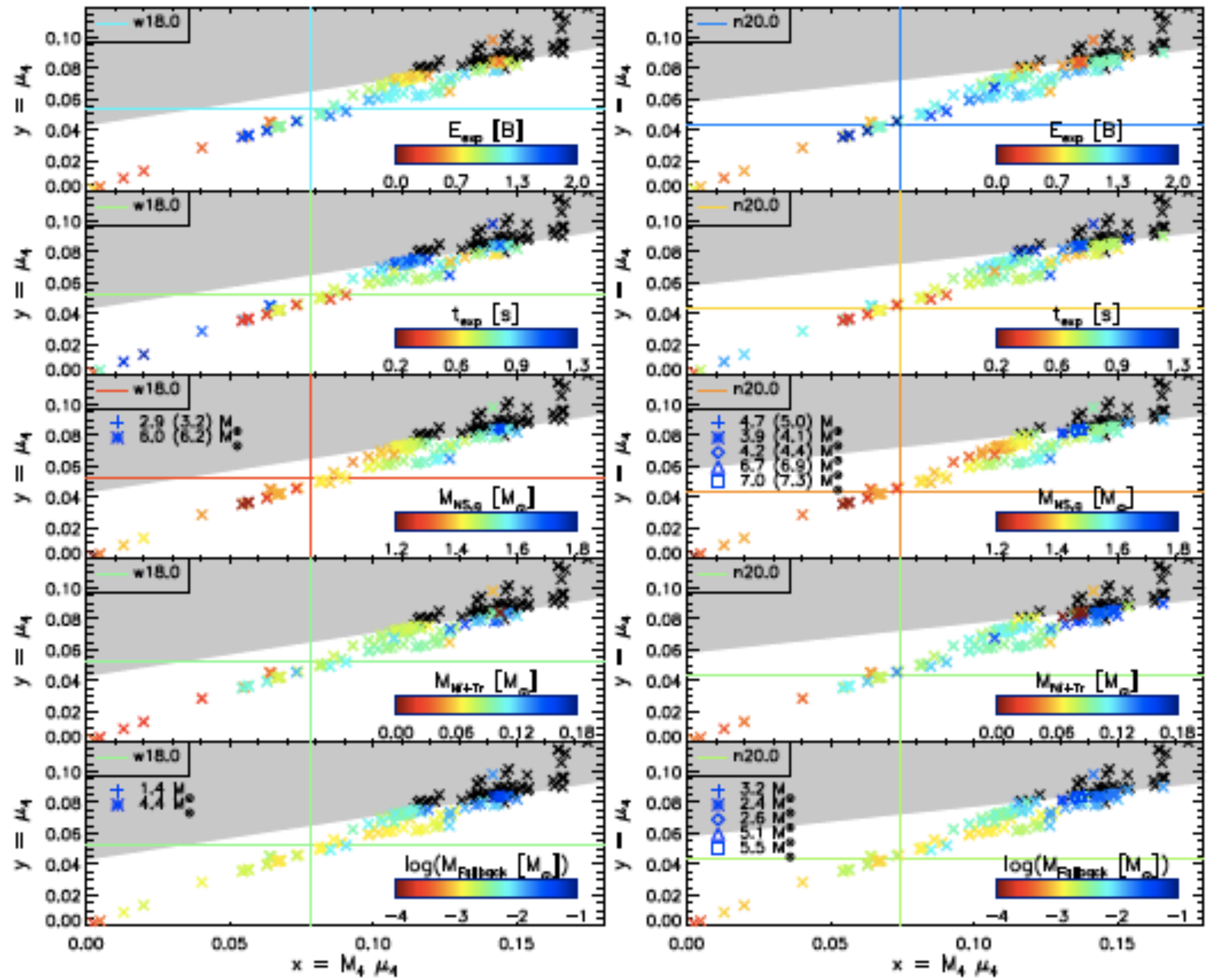
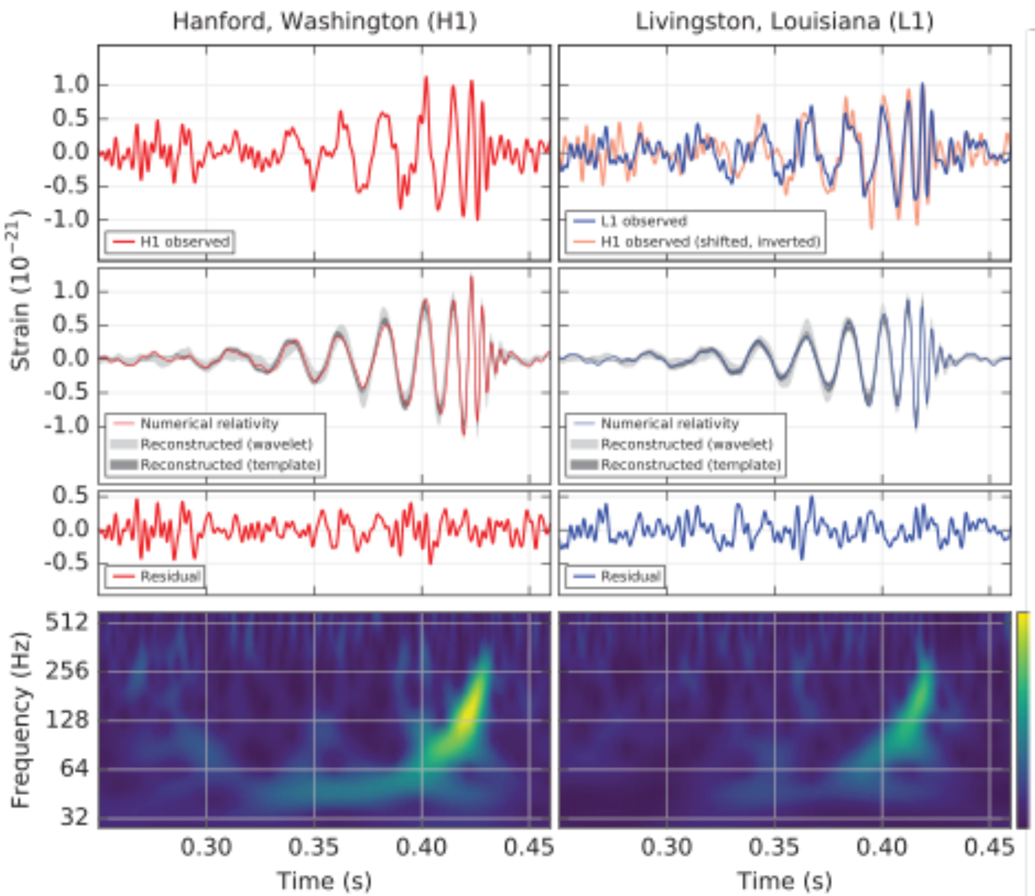
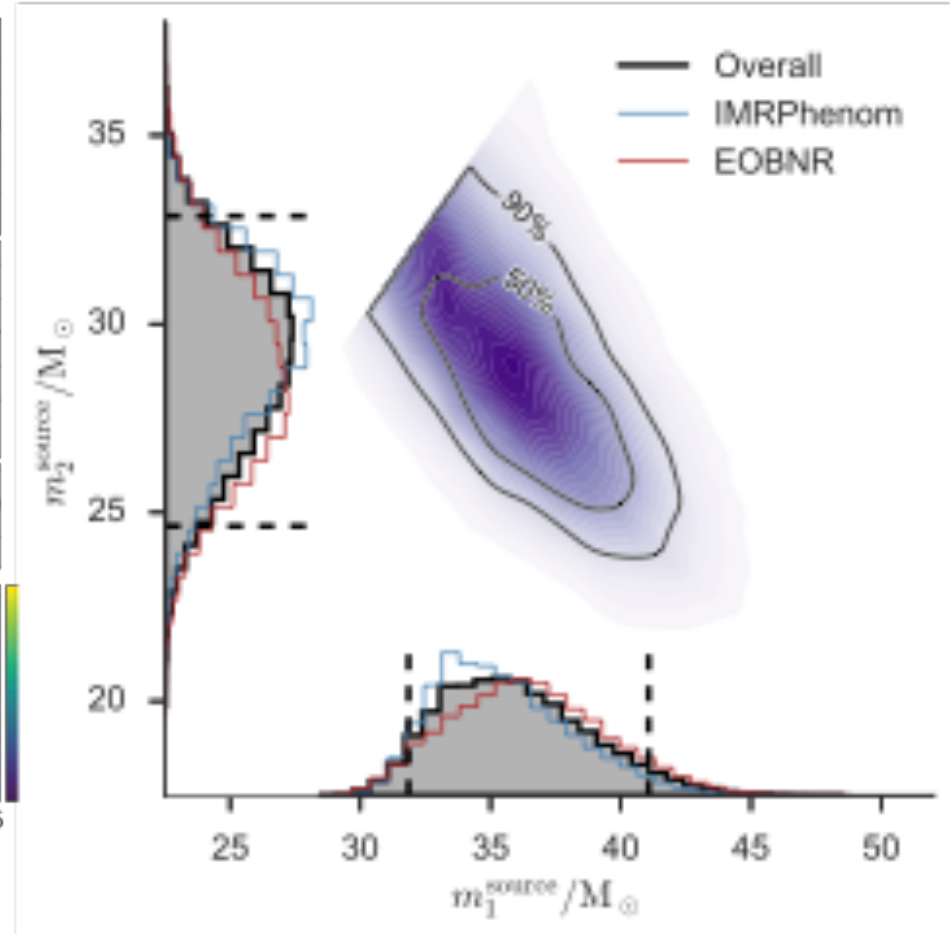


FIG. 12.— Explosion energies (1 B = 1 bethe = 10^{51} erg), post-bounce explosion times, gravitational neutron-star masses ($M_{ns,g} = M_{ns,b} - E_{\nu,tot}/c^2$), ejected iron-group material (i.e., ^{56}Ni plus tracer masses), and fallback masses (*from top to bottom*) of the s2014 series and the supplementary low-mass progenitors with $M_{ZAMS} < 15\,M_\odot$ for calibration models w18.0 (*left*) and n20.0 (*right*) in the x-y parameter plane. Black crosses correspond to BH formation cases, colored crosses to successful explosions. In the middle and bottom panels, the blue (partly overlapping) symbols correspond to fallback SNe with estimated BH masses (baryonic masses in parentheses) and fallback masses as listed in the legends. The horizonal and vertical lines mark the locations of the calibration models with the colors corresponding to the values of the displayed quantities.

2. On the progenitor of GW150914





- LIGO detected gravitational wave
- Merger of two BHs : ~ 36$M_\odot$ and 29$M_\odot$

What can we learn from GW observations ?

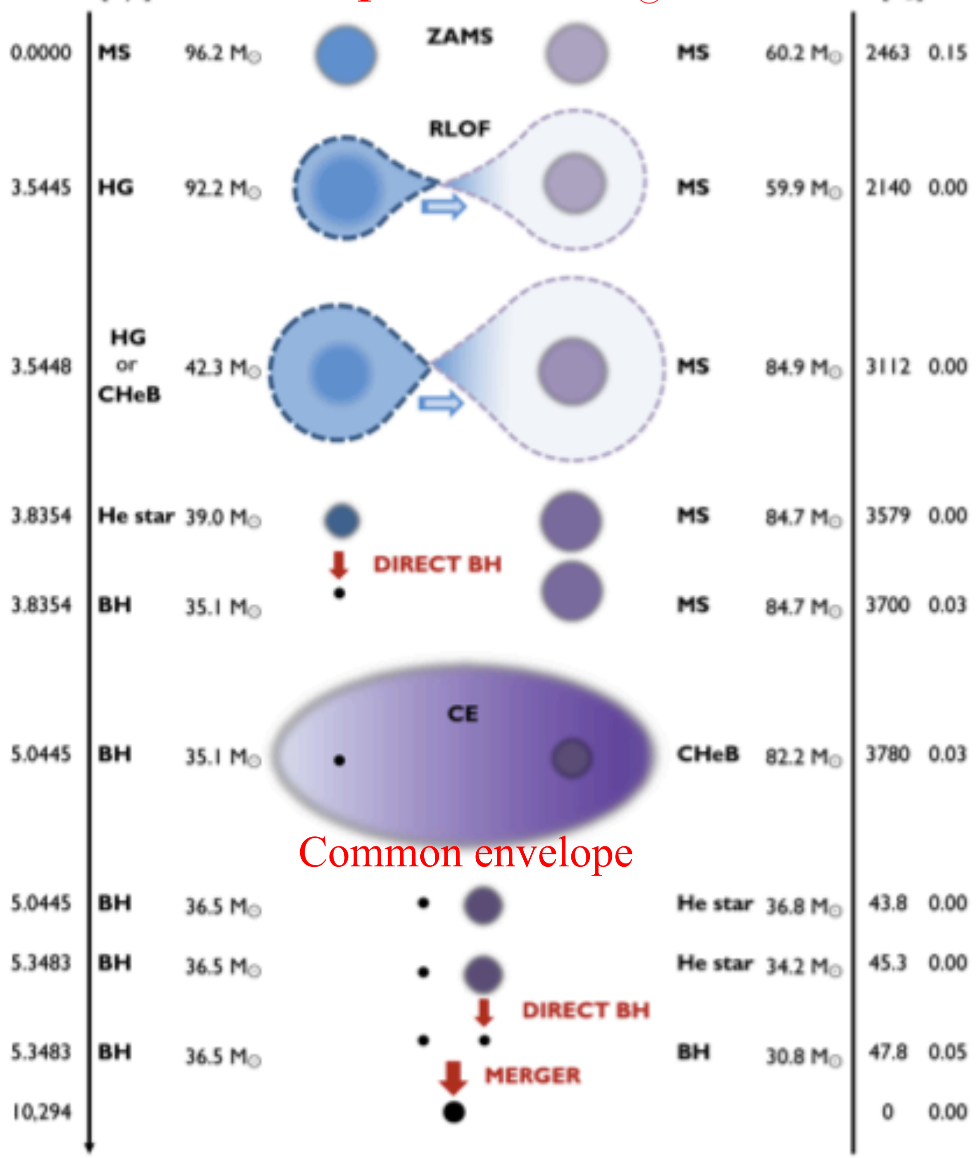
- (Failed) SNe
  - Neutrinos may be deteced almost simultaneously
  - Explosion mechanism, EOS
  - Progenitor structure, spin (rotation profile)
- NS-NS (BH) merger
  - With optical counterpart / Short GRB ?
  - EOS, NS mass, NS spin
  - Nucleosynthesis (r-process)
  - Binary evolution
- BH-BH merger
  - Binary evolution (Common envelope
  - Properties of (very) massive stars :
    - mass loss, initial mass function (metallicity dependence
    - Spin (angular momentum transfer

Important for massive star evolution but uncertain

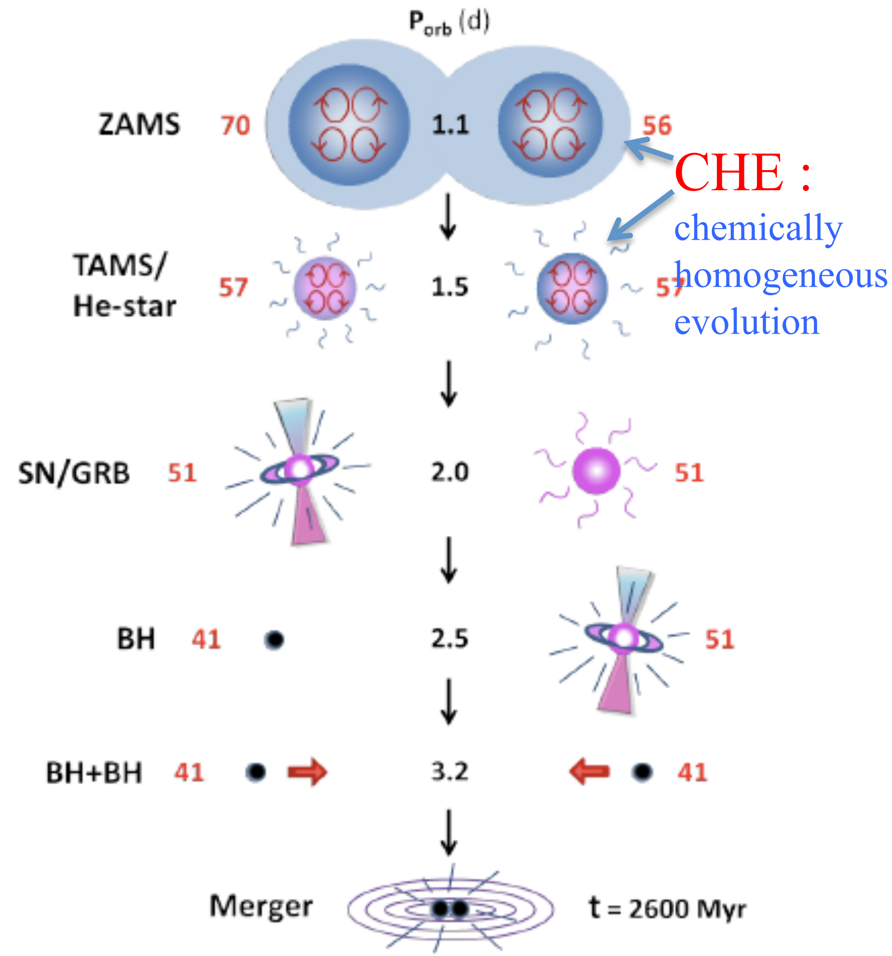
GW150914 : forming scenario

Belczynski +2016 : A possible one

Metal poor : $0.03Z_{\odot}$



Marchant +2016 : no CE phase



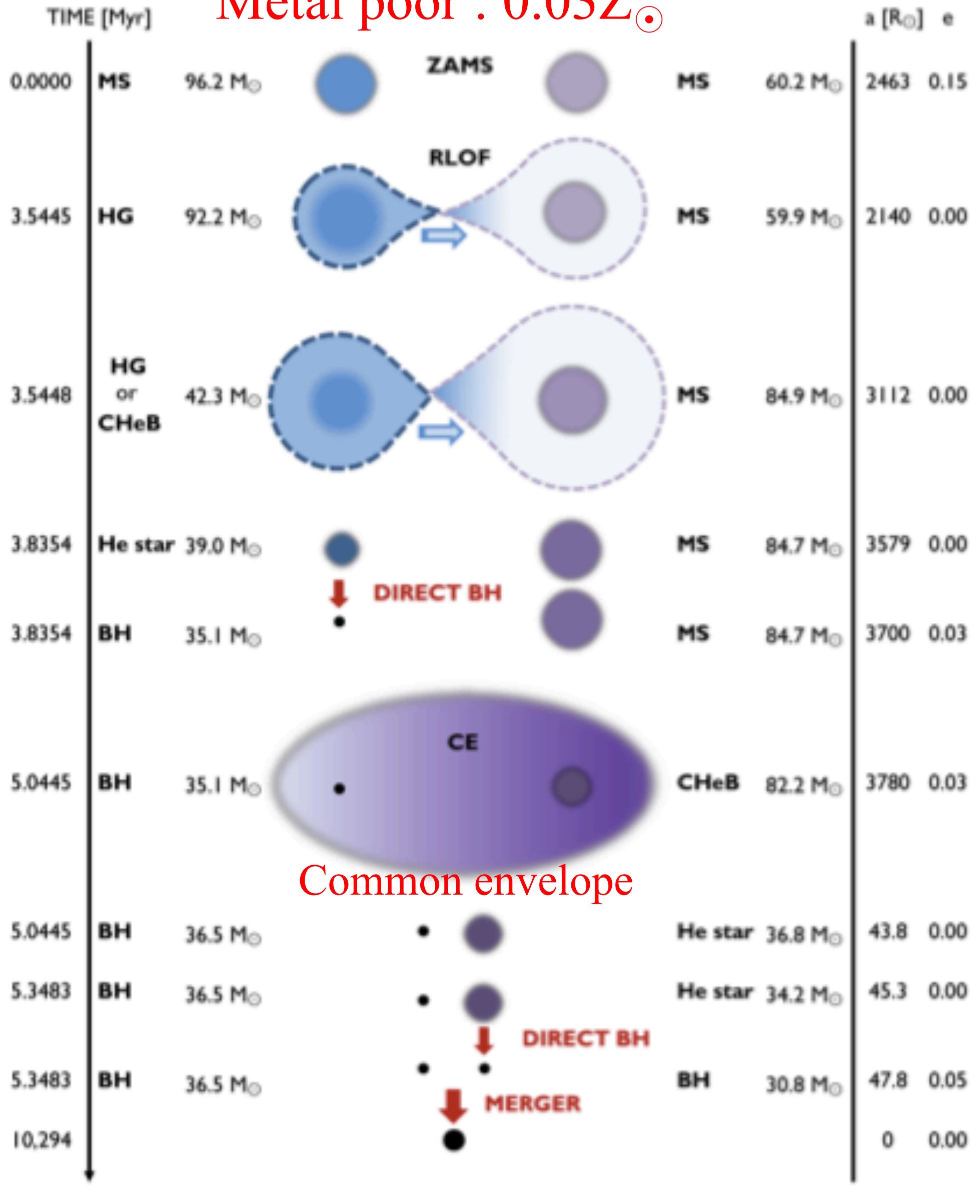
Ends up an equally massive BH+BH

Critically spinning ?

GW150914 : forming scenario

Belczynski +2016 : A possible one

Metal poor : $0.03Z_\odot$



Woosley 2016, arXiv:1603.00511

- first, he rejected a single star model
- negative to Fermi/GBM transient

A binary scenario

Compared with the model left

- suggested that a larger metallicity $Z = 0.1Z_\odot$ might be allowed

e.g., 90M + 70M pair

90M ➡～40M He star through RLOF + mass-loss

70M ➡～30M He core + H-envelope

These stars form a CE and then lose most H envelope during the CE.

After CE, the separation < 0.2 AU.

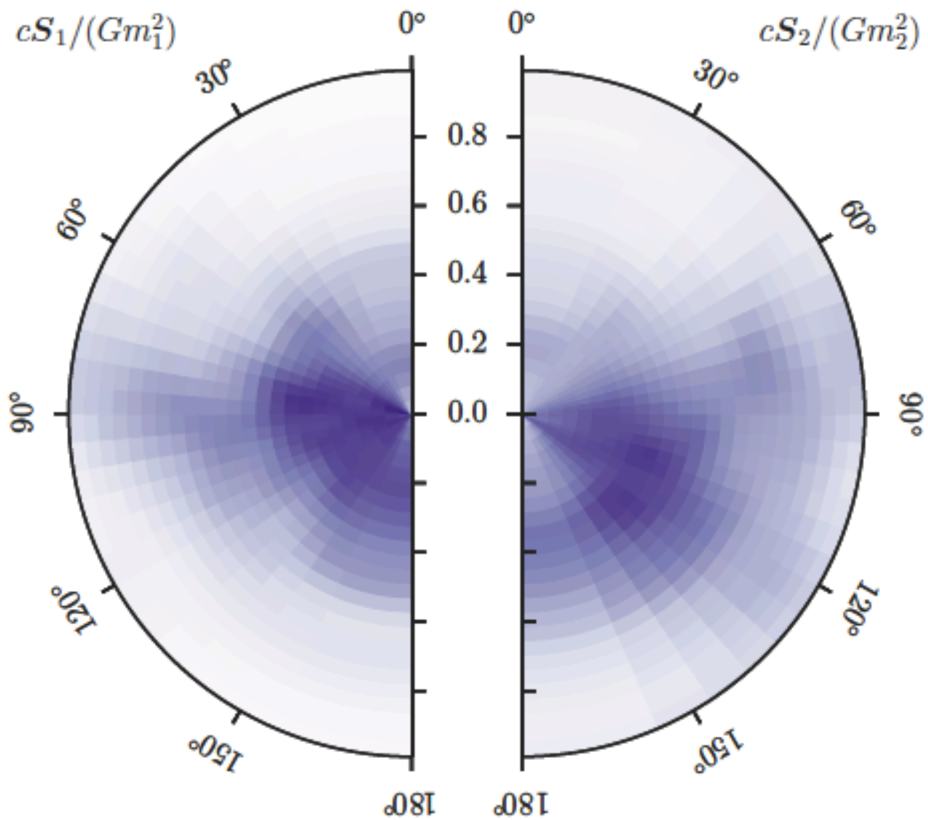
GW150914 : Spin parameter of each BH

arXiv: 1602.0384

- spin parameter
  $a = J/J_{max} = cJ/(GM^2)$

- Observation showed that two BH are not critically spinning

- They are rather slow spinner
  - $a_1 < 0.7$
  - If their spins are aligned, $a_1<0.2$, $a_2<0.3$

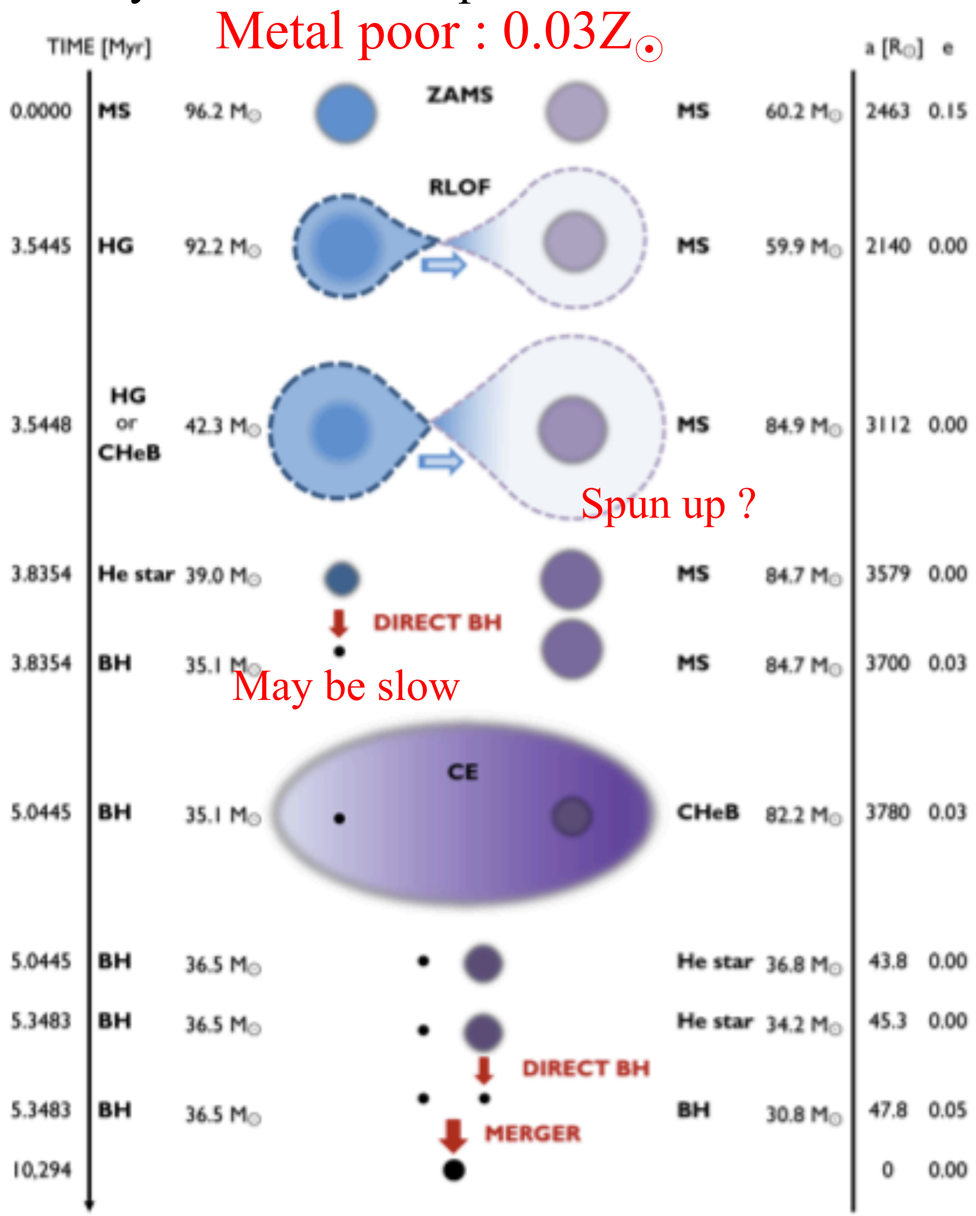


- So we are studying how such slow spinning BH can be produced after stellar evolution

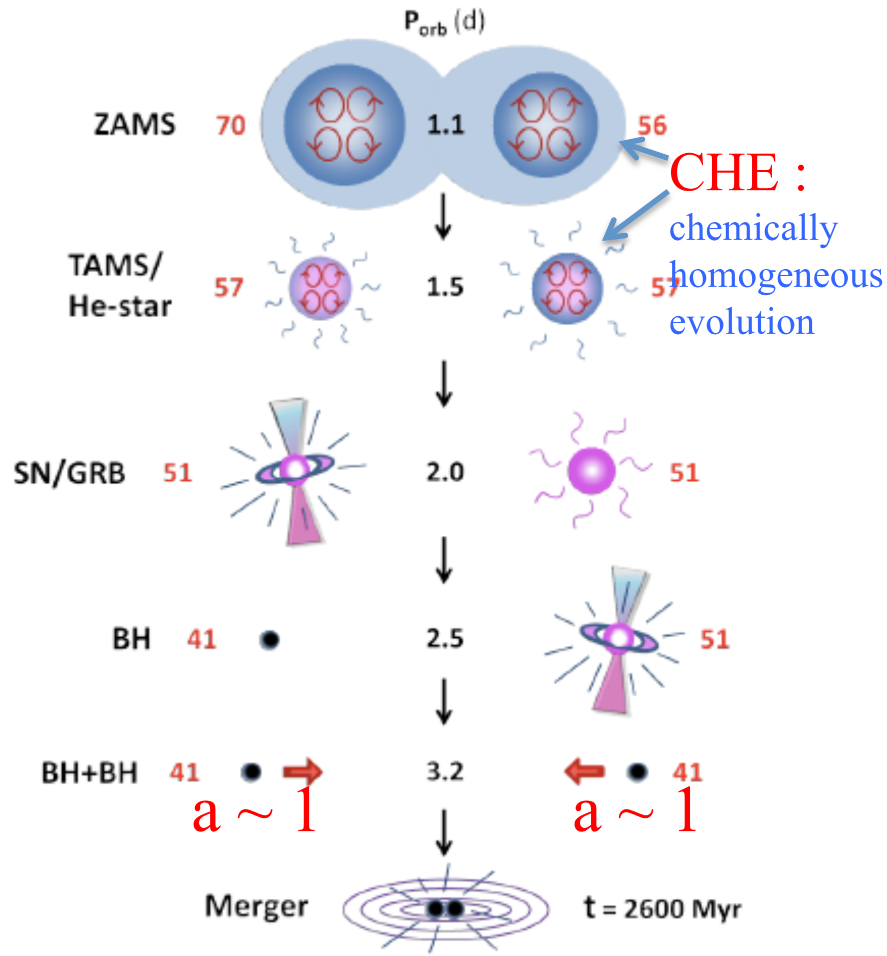
(Takahashi, Umeda, Yoshida 2016 in prepaparation)

GW150914 : forming scenario

Belczynski +2016 : A possible one



Marchant +2016 : no CE phase



Fast spinner

Rotational evolution of a Single star leaving a massive BH

Koh Takahashi, H.U., T. Yoshida (2016, in prep)

- It is important to understand the property of single stars even though GW progenitors might have evolved in binary.
- We calculate for
  - Mass : 60, 90 $M_\odot$
  - Metallicity : 0, 0.1 $Z_\odot$
  - Rotation : 20% (typical), 50% (fast) of V_{Keplar}
  - with/without Spruit-Taylor (ST) dynamo (Spruit 99, 02)
- ST-dynamo : (If this really exists or not, is One of the most important issues in massive stellar evolution theory
  - provides efficient angular momentum transfer in a radiative (c.f. convective) region
  - physically not strongly supported
  - But this or this kind of mechanism may be required to avoid too fast initial rotation of Neutron Stars (Pulsars)

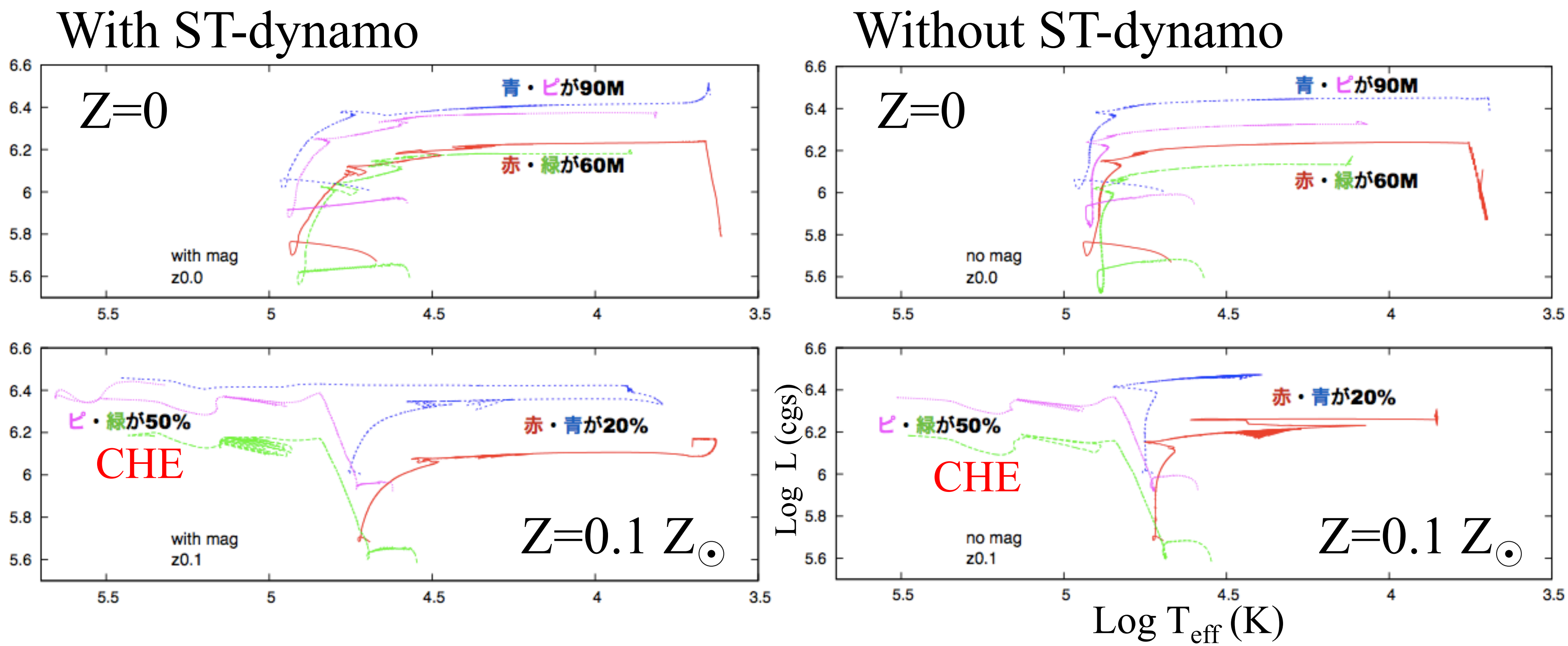
Takahashi et al. 2016: Results

Model name	Initial mass ($M_\odot$)	Final mass ($M_\odot$)	Helium core mass ($M_\odot$)	CO core mass ($M_\odot$)
m60o20z0	60	51.20	37.35	32.18
m60o50z0	60	42.34	32.89	27.71
m90o20z0	90	77.31	62.18	55.15
m90o50z0	90	61.88	46.97	40.15
m60o20z0.1[1]	60	45.90	29.26	-
m60o50z0.1[2]	60	32.35	32.35	31.69
m90o20z0.1[2]	90	52.80	52.80	49.47
m90o50z0.1[2]	90	42.75	42.75	38.10
m60o20z0	60	50.04	37.14	31.28
m60o50z0	60	37.85	30.43	24.71
m90o20z0	90	72.58	55.64	48.64
m90o50z0	90	54.82	43.89	37.50
m60o20z0.1	60	44.17	39.20	33.29
m60o50z0.1[2]	60	30.50	30.50	25.95
m90o20z0.1[1]	90	81.25	54.79	-
m90o50z0.1[2]	90	42.92	42.92	37.57

He core mass is about 29 ~ 62 $M_\odot$

This will be a BH mass if these stars will be in a common envelope with another star.

Takahashi et al. 2016: HR-diagram

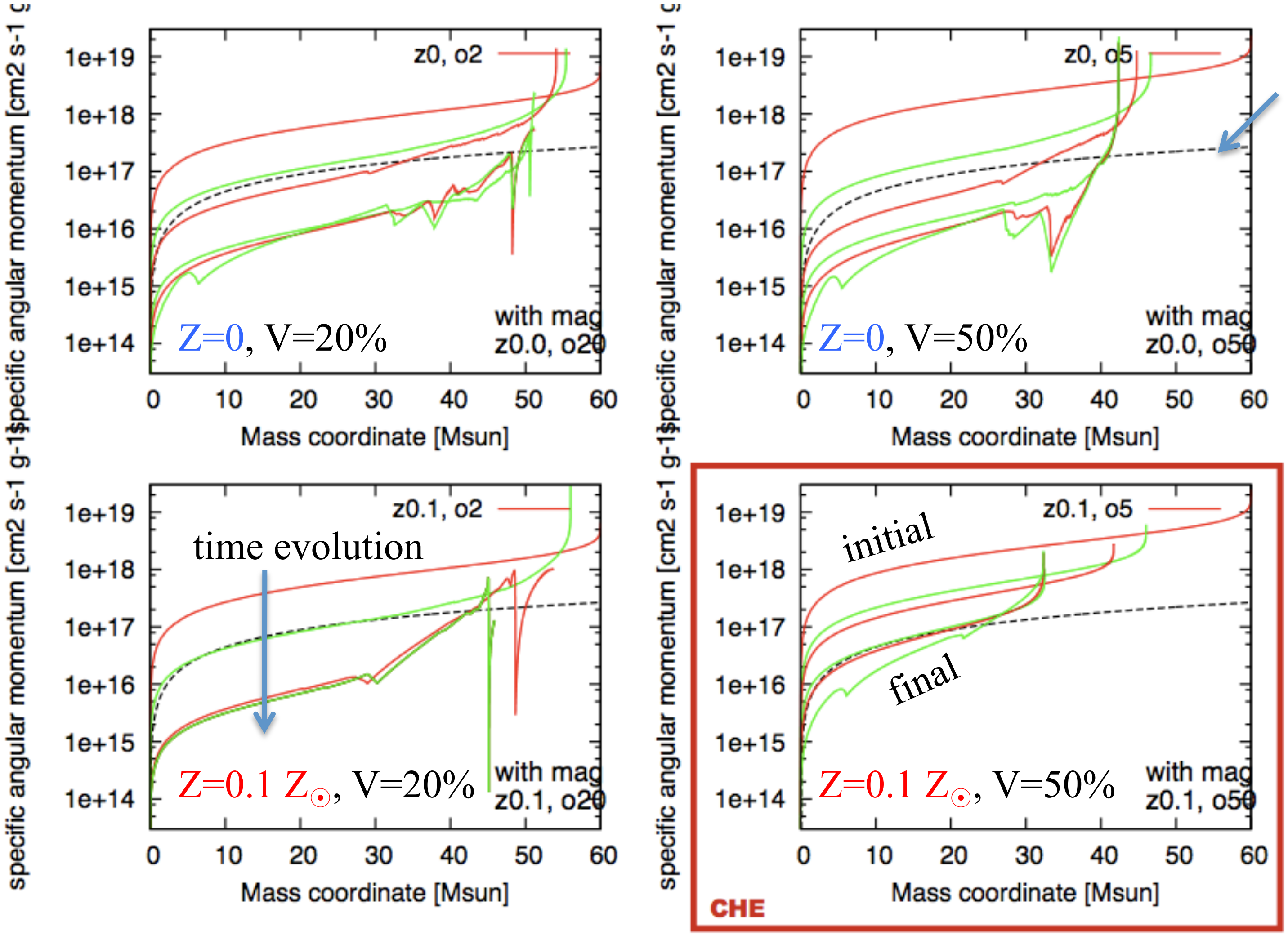


Stars in CHE evolve directly from main sequence to Wolf-Rayet.
Z=0 models do not become CHE because angular momentum is ejected during pre-main sequence stages.

Fast (50%) Z=0.1 $Z_\odot$ models become CHE.

Takahashi et al. 2016: Specific angular momentum

$60M_{\odot}$, with ST-dynamo Ang. Momentum is removed with mass-loss



dashed : spe.ang.momentum for Last stable orbit (a=1)

Consistent with Yoon & Langer 05 Heger & Woosley 06

Only the model becoming CHE can maintain fast rotation, a~1

Takahashi et al. 2016: Specific angular momentum

with ST-dynamo

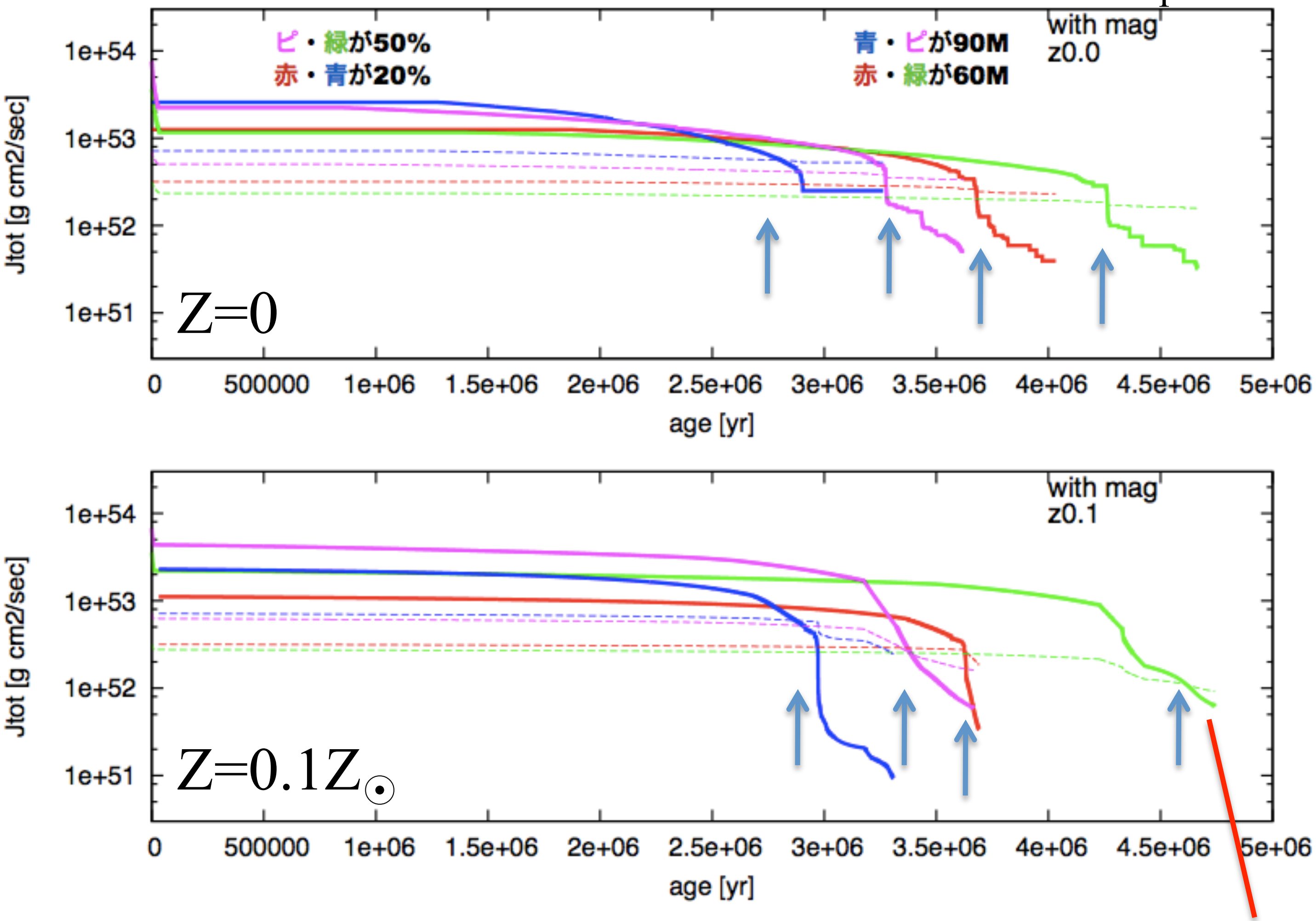
Only the model becoming CHE can maintain fast rotation, a~1

without ST-dynamo

All models may produce GRBs if $j \sim j_{last}$ is the necessary condition for GRBs (this is inconsistent with observations)

Takahashi et al. 2016: Total angular momentum, J

With ST-dynamo, (60, 90$M_\odot$), (20, 50% V_{Kep})



Solid lines: results

Dashed lines: critical (a = 1)

The models lose angular momentum with mass-loss and cross the critical line at the positions marked by ↑

Only this model (60$M_\odot$, 50%) has a~1 at the end

Takahashi et al. 2016: Spin parameter

Group	Model name	Initial mass ($M_\odot$)	Final mass ($M_\odot$)	Helium core mass ($M_\odot$)	CO core mass ($M_\odot$)	Final spin parameter	Spin para. of the He core	Spin para. of the CO core
ST-dynamo	m60o20z0	60	51.20	37.35	32.18	1.703e-1	5.633e-2	5.525e-2
ST-dynamo	m60o50z0	60	42.34	32.89	27.71	2.046e-1	5.134e-2	5.524e-2
ST-dynamo	m90o20z0	90	77.31	62.18	55.15	4.745e-1	3.595e-2	3.376e-2
ST-dynamo	m90o50z0	90	61.88	46.97	40.15	1.507e-1	4.768e-2	4.772e-2
ST-dynamo	m60o20z0.1[1]	60	45.90	29.26	-	1.84e-1	4.198e-2	-
ST-dynamo	m60o50z0.1[2]	60	32.35	32.35	31.69	6.767e-1	6.767e-1	5.908e-1
ST-dynamo	m90o20z0.1[2]	90	52.80	52.80	49.47	3.824e-2	3.824e-2	3.764e-2
ST-dynamo	m90o50z0.1[2]	90	42.75	42.75	38.10	3.659e-1	3.659e-1	2.846e-1
No ST-dynamo	m60o20z0	60	50.04	37.14	31.28	8.521e-1	7.600e-1	7.593e-1
No ST-dynamo	m60o50z0	60	37.85	30.43	24.71	9.680e-1	9.226e-1	8.816e-1
No ST-dynamo	m90o20z0	90	72.58	55.64	48.64	7.674e-1	6.984e-1	7.355e-1
No ST-dynamo	m90o50z0	90	54.82	43.89	37.50	8.615e-1	8.37e-1	8.055e-1
No ST-dynamo	m60o20z0.1	60	44.17	39.20	33.29	2.841e-1	2.848e-1	3.030e-1
No ST-dynamo	m60o50z0.1[2]	60	30.50	30.50	25.95	1.119e0	1.119e0	9.747e-1
No ST-dynamo	m90o20z0.1[1]	90	81.25	54.79	-	1.297e0	6.819e-1	-
No ST-dynamo	m90o50z0.1[2]	90	42.92	42.92	37.57	8.953e-1	8.953e-1	7.928e-1

Takahashi et al. 2016: Summary

- We studied rotational evolution for Z=0, 0.1 $Z_{\odot}$, M=60, 90$M_{\odot}$ and V=20, 50% V_{Kep}
- If no mechanism like ST-dynamo, massive BHs should typically have a large spin parameter, a >~0.7, and can be tested through GW detections.
- With ST-dynamo, typical (single) BHs should be slow spinner including Pop III (Z=0) ones.

- There is no "radiative" mass-loss for Z=0, so no angular momentum loss associated with this.

  However, surface velocity of a Z=0 star continuously exceeds the break up velocity

  ➡ mass loss & making slow spinner

3. The progenitor of SN1987A

- Since this is a neutrino conference (@Koshiba hall), I think, it is relevant to talk about SN1987A.

- Purpose of this presentation is NOT to give full explanations, but

  to note that we still don't fully understand about SN1987A progenitor (because it is quite complicated) even after 30 years!

超新星 SN1987A

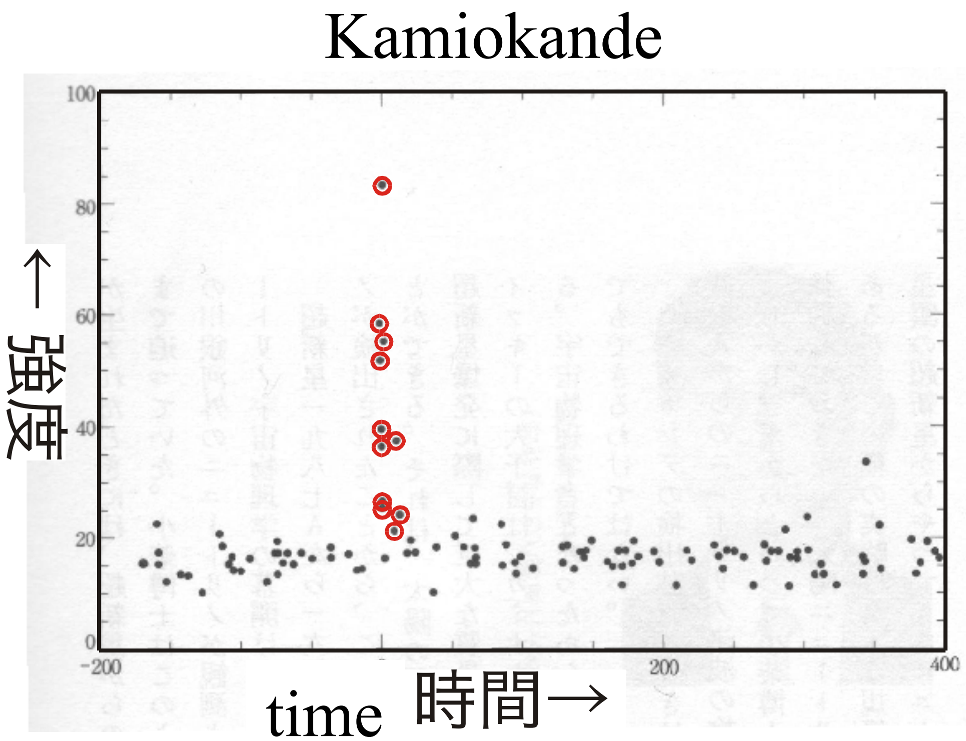
久々に肉眼で見える超新星がマゼラン雲 (LMC) に出現

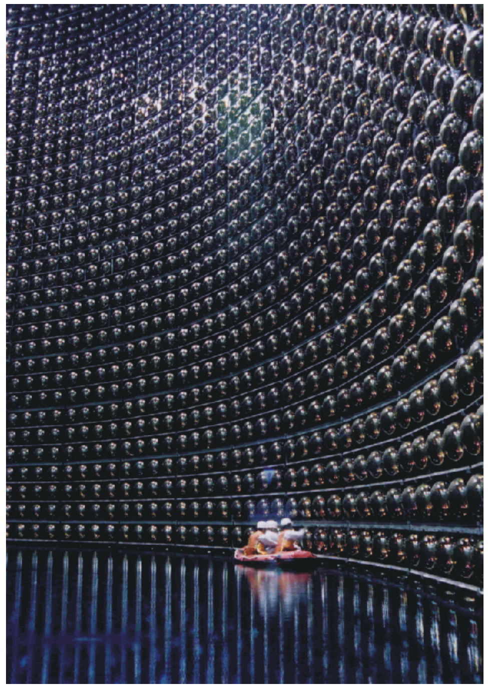
爆発前
1984 年 2 月 5 日

爆発後
1987 年 3 月 8 日

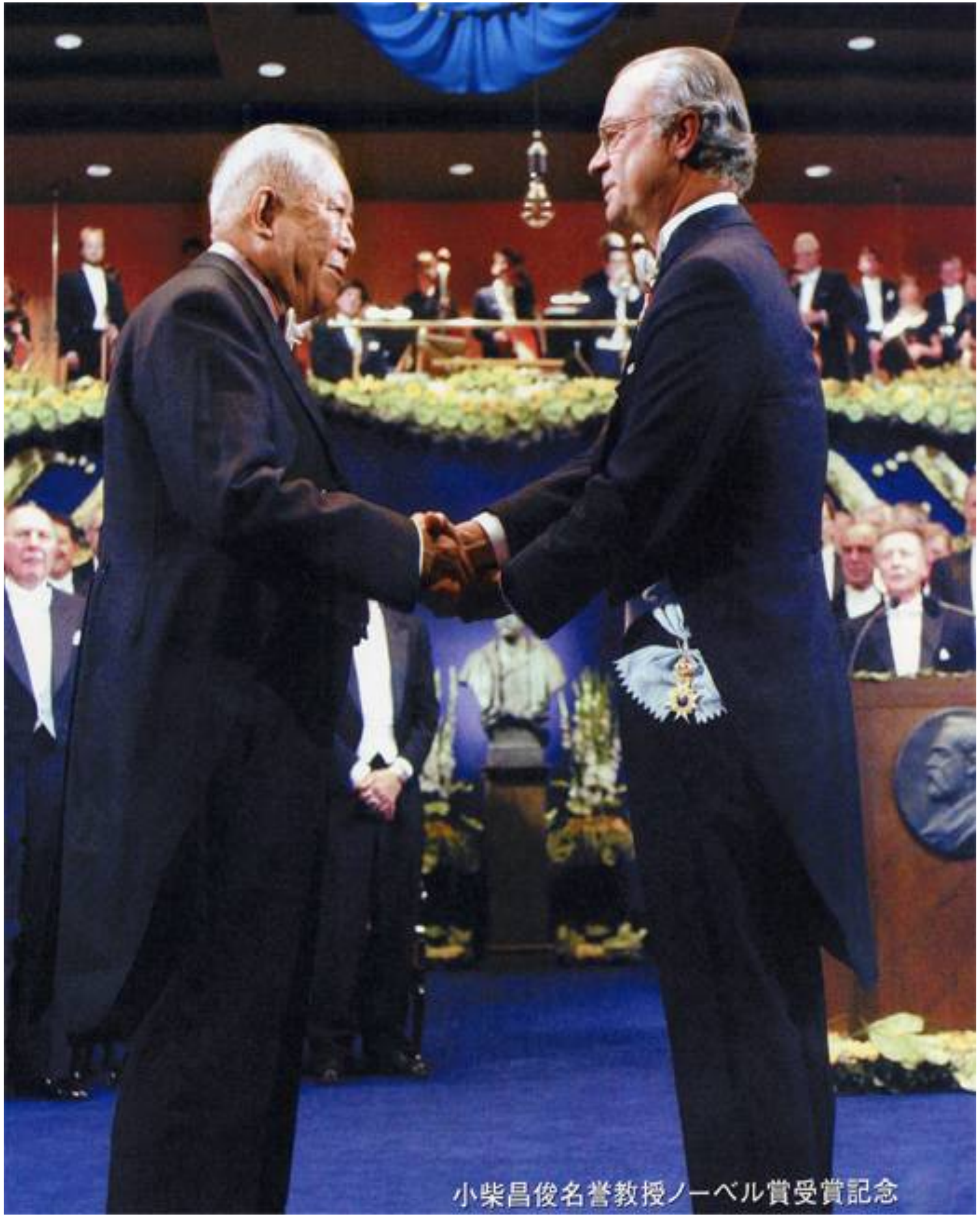
Neutrinos from SN1987A

- Kamiokande detected
- 11 in 13 seconds
  10 billion neutrinos per 1cm^2 on the earth
- Supernova explosion theory was roughly confirmed !





Prof.
Koshiba

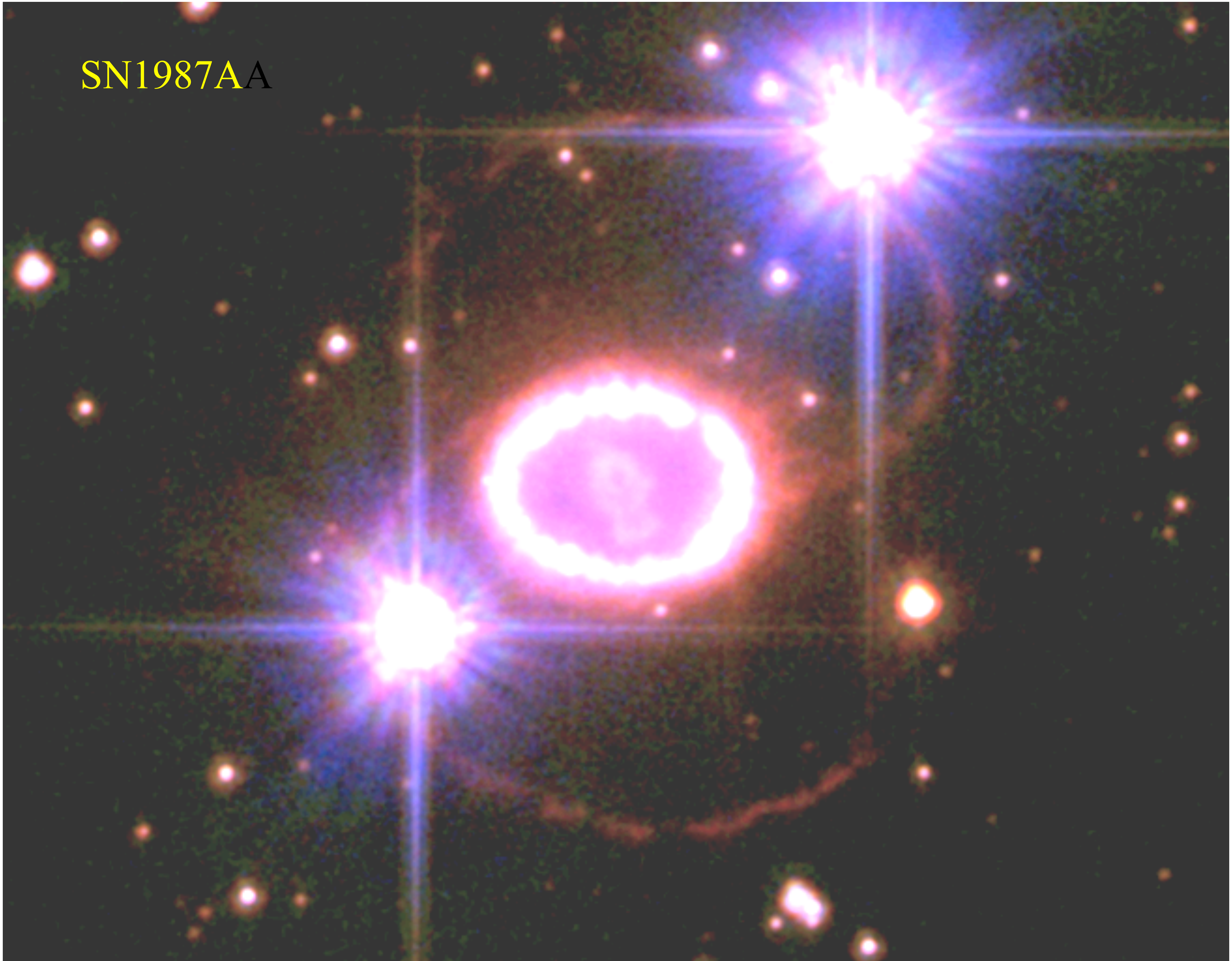


And, Koshiba-hall was built

Mysteries about SN1987A progenitor

- It was blue before explosion！
- 3 rings (considered an evidence that the progenitor was once red and turned into blue)
- Ejecta seems to be asymmetric
- Abundance anomary（He-rich

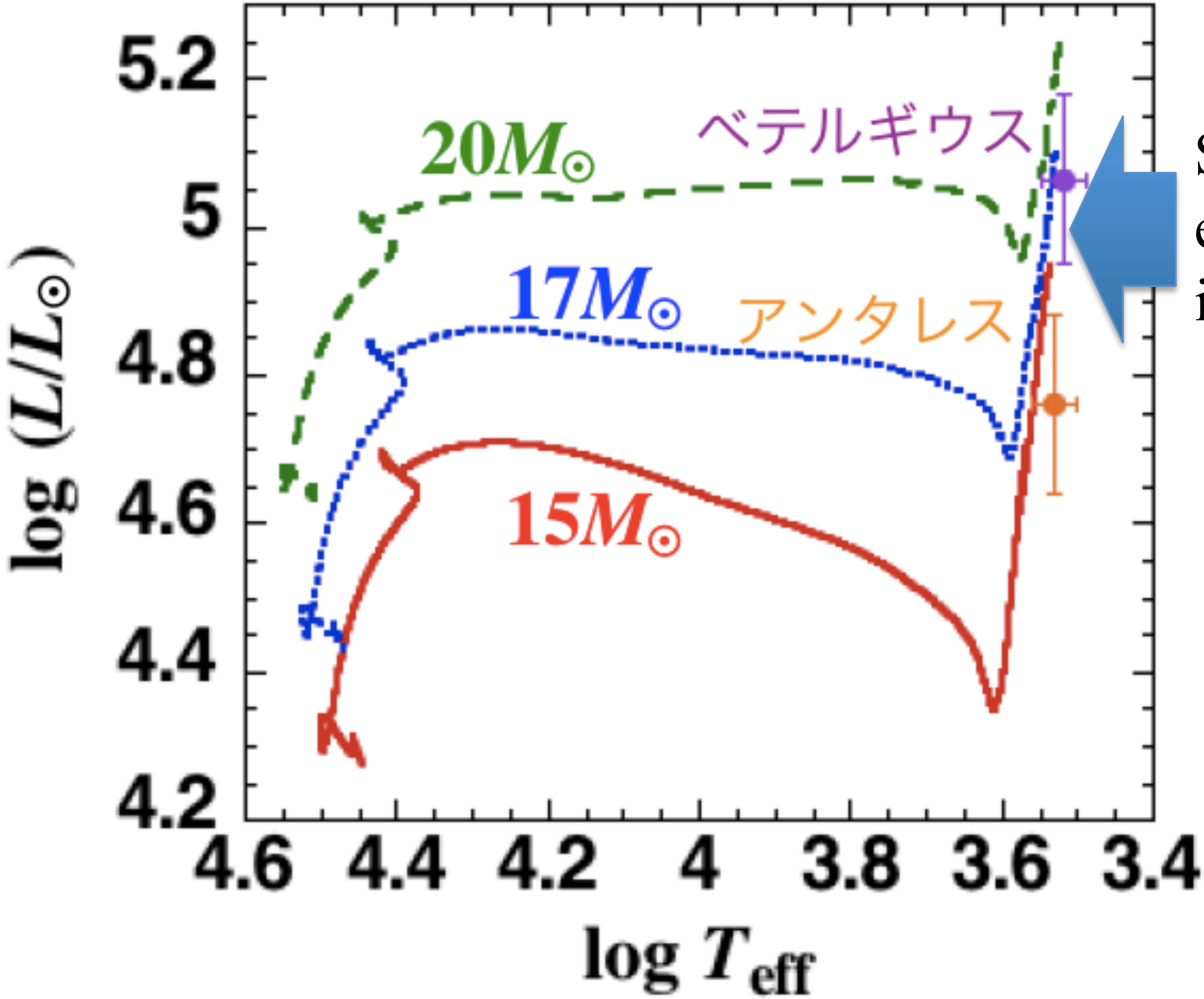
- These peculiarities haven't been fully understood


SN1987AA

HR-diagram: Normal stellar evolution

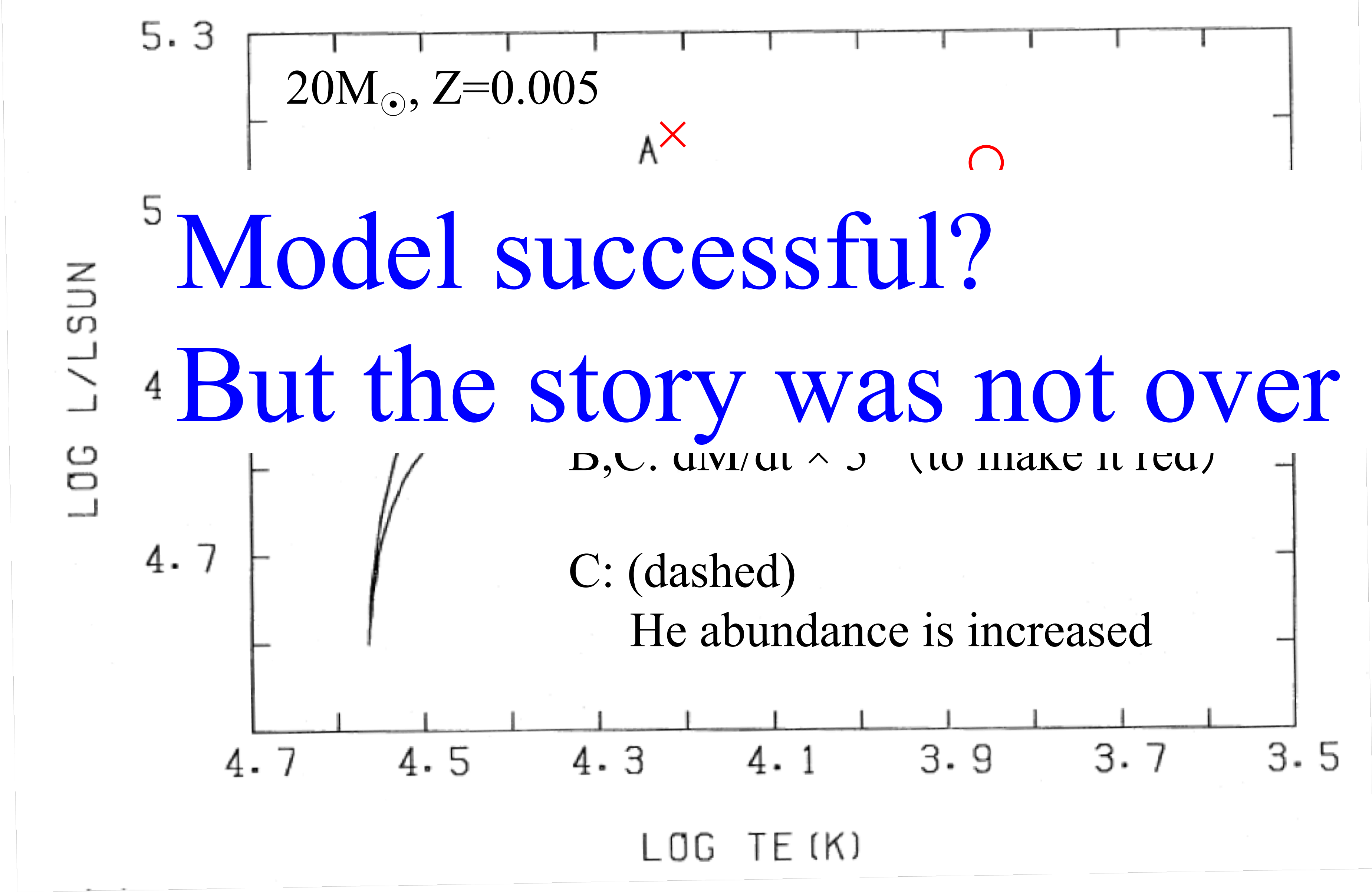
Blue:
smaller radius

Red:
larger radius



Supernova
explosion
in Red

A single star model (Saio, Nomoto, Kato 1988)



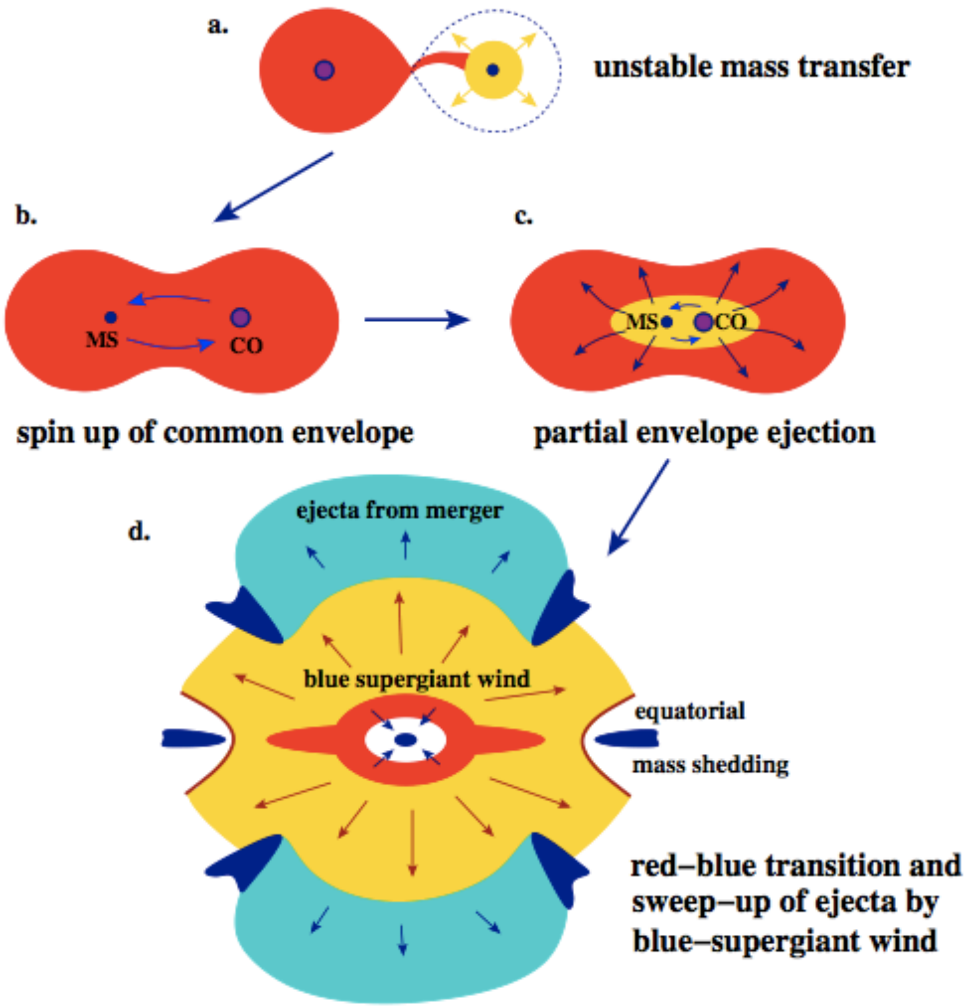
Model successful?

But the story was not over

SN1987A : single or binary?

- Saio+1988 result suggested that He-rich may be realized by rotational mixing
- But no fast-rotating model has been successful
  - Fast rotation ➡ larger core ➡ tend to be Red
    - Langer group, Woosley group – unpublished
  - We have also tried many and confirmed that single fast rotating models do not work.
- Alternative model : binary merger model
  - Podsiadlowski and collaborators

A merger (spiral-in) model for formation of three rings
(Morris and Podsiadlowski 2007)

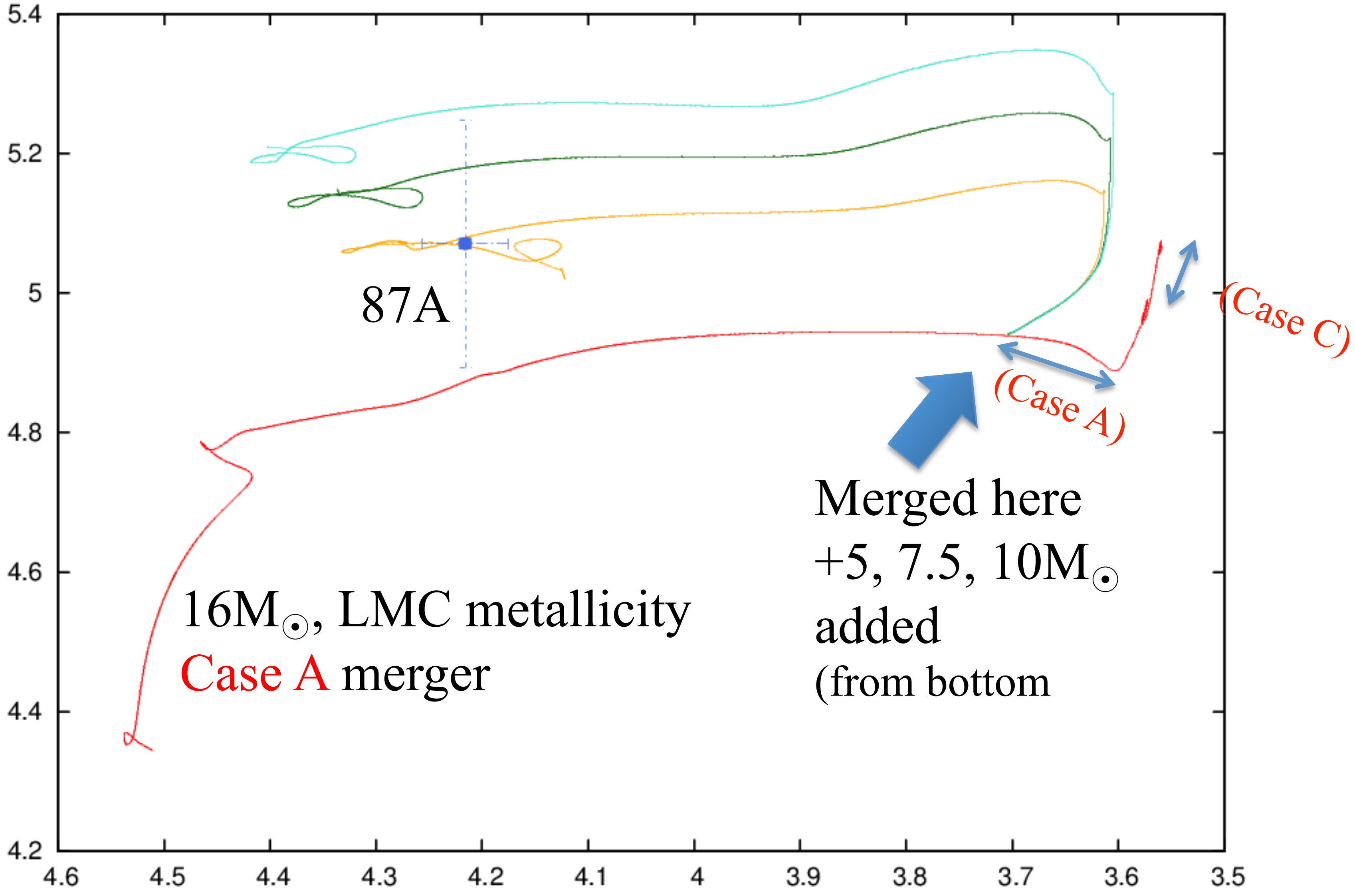


It simultaneously makes the primary turns from Red to Blue
by giving mass, energy and angular momentum.
(Podsiadlowski 1992)

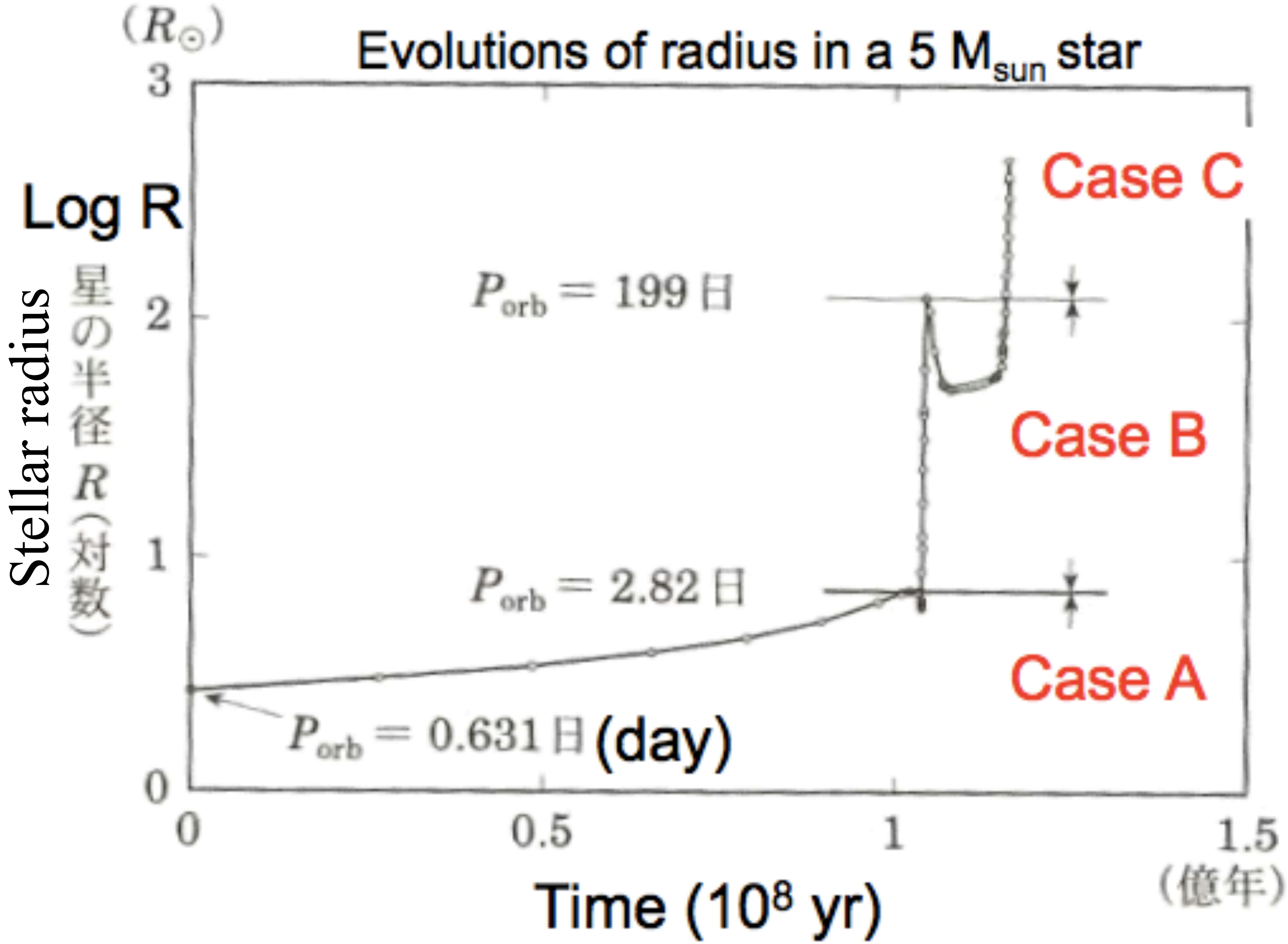
But his calculation didn't include rotation.

Rotation effects in the merger (spiral-in) model :

Urushibata +2016 in preparation



Cases of binary mass transfer

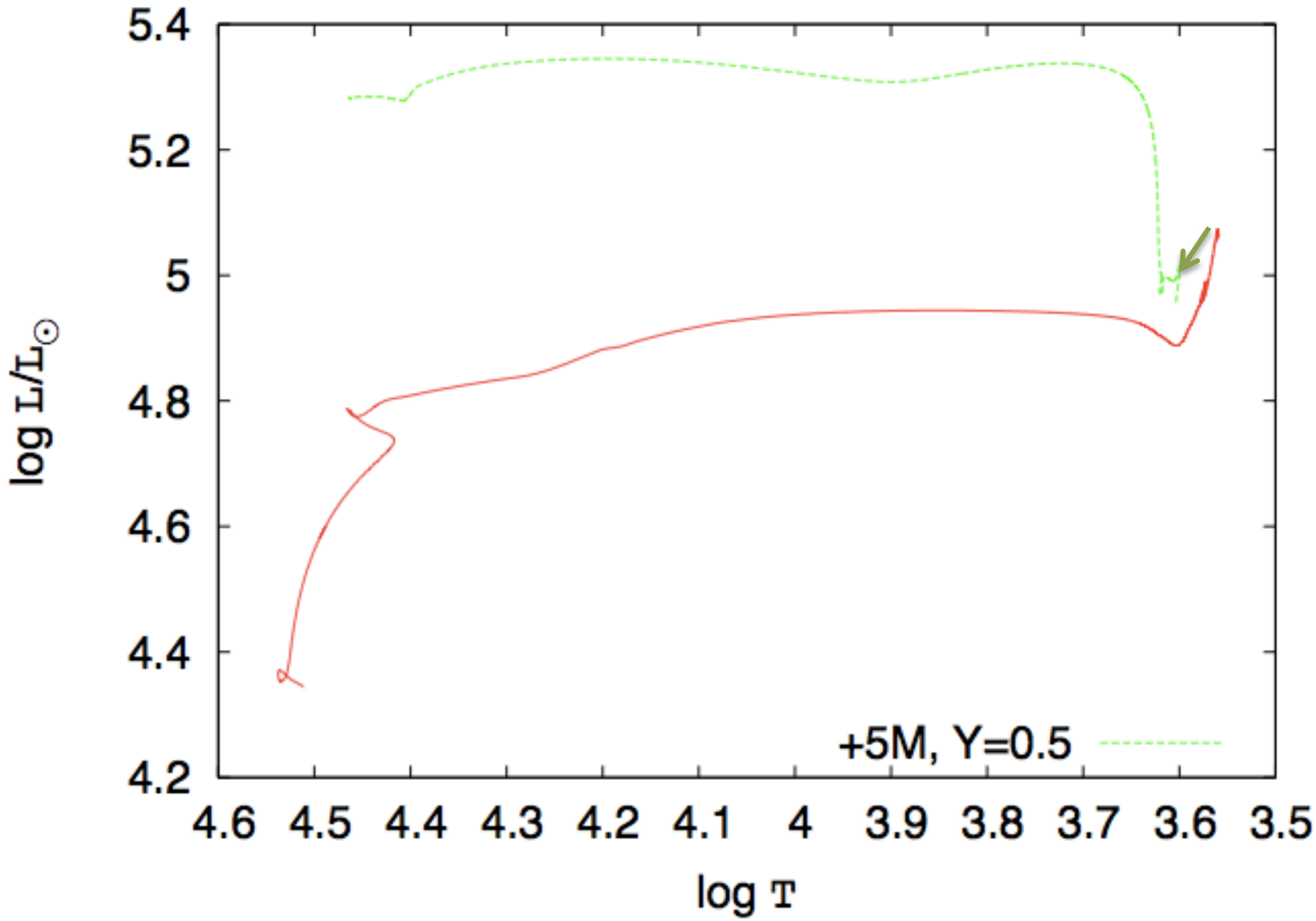


Urushibata +2016

- For a Case A merger just adding mass of $5M_\odot$ makes the progenitor from Red to Blue
- During the merger, angular momentum also should be added
  - Rotation in general gives negative effects to make the star blue
- From the size of the Ring, Case C merger may be better for the SN1987A model
- Our results revealed that just adding mass is not enough for Case C to make the star blue

Urushibata +2016: Case C merger + He rich envelope

(Preliminary): can be blue, but the He enhancement can't be realized only with rotational mixing ➡ merging induced mixing?



Summary

- Topic1: explodability may be determined by two pre-collapse parameters M_4 and μ_4 (Or we need at least two)
  - Though the results depend on PNS models unfortunately
  - M = 10 ~ 22 and 25~27 $M_\odot$ may explode by neutrino driven mechanism
- Topic2: Angular momentum transfer is very important in discussing massive star evolution, and GRBs
  - GW observations may potentially prove the rotational properties of massive stars
- Topic3: SN1987A is still mystery
  - Red to Blue evolution may require merger of a M ~ 5$M_\odot$ star, and matter mixing induced by the merging to make the star He-rich